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Nonplanarity and the protonation behavior of porphyrins

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^{1}H NMR studies of the protonation of highly nonplanar porphyrins with strong acids reveal the presence of the previously elusive monocation, and show that its stability can be related to the amount of saddle distortion induced by protonation; the amount of saddle distortion for a porphyrin dication is also found to correlate well with the rate of intermolecular proton transfer.

Molecules based on the porphyrin framework (**1**) are of considerable importance because they are used in a number of applications (e.g. catalysis) and because they are cofactors in many biological systems.[1] As a group, porphyrins frequently display unusual and interesting behavior, and this is the case when they are protonated with strong acids to form monocations (**2**) and dications (**3**).[2-4] Upon titration with strong acids, porphyrins [especially tetraarylporphyrins such as tpp (**4**)] form much smaller amounts of monocation than do simple dibasic systems.[2,3] In

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addition, the rate of proton exchange between the free base and dication of tpp is much slower[4] than in octalkylporphyrins [as typified by oep (**5**)], a somewhat unexpected finding as the latter have more electron-releasing substituents. It has been speculated that the instability of porphyrin monocations may be explained, at least in part, by a significant nonplanar distortion upon formation of the monocation,[5] and also that the slow proton exchange rate seen for tpp might be related to the very nonplanar structure of the dication of this porphyrin.[4] However, the extent to which nonplanar distortions determine the protonation behavior of this important group of molecules has not been investigated in any detail. Herein, we describe ^{1}H NMR studies of the very nonplanar porphyrins oetpp (**6**) and t(Bu^t)p (**7**) and the standard porphyrins tpp and oep which show how strongly nonplanar distortions influence the protonation properties of porphyrins.

To examine the protonation of porphyrins **4-7**, the chloride, trifluoroacetate, and picrate (2,4,6-trinitrophenolate) salts of the dications were prepared and ^{1}H NMR spectra measured as they were titrated with the corresponding free base porphyrins. This procedure is equivalent to the direct titration of free base porphyrins with trifluoroacetic acid reported in earlier NMR studies[4,6,7] but was found to be more convenient when working with aqueous acids. Before carrying out the titrations, the purity of the dications was checked using ^{1}H NMR spectroscopy. In the case of the picrate complexes, an upfield shift was seen for H_{meta} of the picrate anion versus the free acid ($\Delta\delta$ = 1.4 - 1.9 ppm) unambiguously confirming the presence of picrate anions bound to the porphyrin dication.

As noted earlier, it has been speculated that nonplanarity of the porphyrin macrocycle might explain the unexpectedly high activation energy for proton exchange between the free base and dication of tpp.[4] To investigate this proposal, variable temperature ^{1}H NMR spectroscopy was used to determine the activation energies for proton exchange (abbreviated as $\Delta G^{\ddagger}_{EX}$) for porphyrins **4-7**. The results of these studies (Table 1) show that $\Delta G^{\ddagger}_{EX}$ varies significantly as a function of the porphyrin and the anion. In particular, $\Delta G^{\ddagger}_{EX}$ increases in the series oep < tpp < t(Bu^t)p < oetpp. This trend can be related to the amount of saddle distortion (pyrrole tilting) in the

dication as approximated by ΔC_b in Table 1, suggesting that saddle distortion is a key factor in determining the intermolecular proton exchange rates for porphyrins **4-7**.

The inverse relationship between $\Delta G^{\ddagger}_{EX}$ and ΔC_b can be explained in terms of increased saddle distortion reducing the steric repulsions between the protons in the porphyrin core, and therefore decreasing the rate of proton dissociation which is the rate-limiting step for proton exchange.[2,3] Thus, the slowest rates of proton exchange are observed for oetpp, where crystallographic studies reveal extremely nonplanar saddle structures, and the fastest rates are seen for oep where the dications show the least distortion (Table 1). The amount of saddle distortion for a given dication must presumably depend largely upon the amount of steric strain induced by the peripheral substituents.

Figure 1 shows a portion of an NMR spectrum obtained during titration of the oetpp dication picrate salt in CD_2Cl_2. The spectrum was measured at a temperature of 298 K where proton exchange is slow on the NMR timescale. The group of signals at δ 8.6 - 8.4 corresponds to the porphyrin H_{ortho} protons, whereas the signals at δ 7.9 - 7.6 arise from the porphyrin H_{meta} and H_{para} protons. An additional species is present which is not the dication or free base porphyrin. This component is also seen during the titration of oep but not during the titrations of tpp or t(Bu^t)p. The proportion of the third component and its pattern of NMR signals were found to vary according to the anion, solvent, and temperature. Additional studies of the complicated NMR behavior of this species are currently in progress, but the fact that its concentration increases and then decreases during the titration together with the ratio of the picrate H_{meta} to porphyrin H_{ortho} signals (1:4) strongly suggests that it is the monocation **2**. To the best of our knowledge, this is the first time that the monocation of a simple porphyrin system has been observed by NMR spectroscopy.[4,6,7]

Of particular relevance to the present study is the fact that the ability to observe the monocation can be correlated with the amount of saddle distortion the occurs upon protonation of the free base porphyrin to form the dication (last column in Table 1). Put simply, the monocation is not observed for the two porphyrins (tpp and t(Bu^t)p) which undergo the largest amount of saddle

distortion upon protonation. It does not seem to matter whether this distortion occurs from a nominally planar conformation (tpp) or from a very ruffled (pyrrole rings twisted) conformation (t(Bu^t)p).

These findings lend support to the suggestion[5] that large protonation-induced nonplanar distortions decrease the stability of the porphyrin monocation. Most likely, a large saddle distortion of the monocation destabilizes it because the distortion significantly reduces the steric crowding of the unprotonated pyrrole nitrogen atom, which makes the second protonation more energetically favorable than the first. A reasonable assumption made in this model is that a large increase in saddle distortion in the dication indicates a large distortion in the monocation. However, obtaining confirmation of this fact from crystallographic studies will most likely be difficult because of the instability of the monocations. Finally, it should be noted that saddle distortion was only one factor seen to influence the amount of monocation formed during our studies; others included the anion, solvent, and temperature.

The present study shows that the increase in saddle distortion between the free base and dication of porphyrins **4-7** is a good predictor of the stability of the monocation, and that the total amount of saddle distortion in the dications of these porphyrins correlates well with the intermolecular proton exchange rate. It also demonstrates that highly nonplanar model systems can be successfully used to address longstanding questions about the influence of nonplanar distortions on the properties of porphyrins.

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References:

1 K. M. Kadish, K. M. Smith, and R. Guilard (eds.), *The Porphyrin Handbook*, Academic Press, Burlington, MA, 2000.

2. F. Hibbert and K. P. P. Hunte, *J. Chem. Soc., Perkin Trans. II*, 1977, 1624.

3. K. A. Freeman, F. Hibbert, and K. P. P. Hunte, *J. Chem. Soc., Perkin Trans II*, 1979, 1237.

4. R. J. Abraham, G. E. Hawkes, and K. M. Smith, *Tetrahedron Lett.*, 1974, **1**, 71.

5. A. Stone and E. B. Fleischer, *J. Am. Chem. Soc.*, 1968, **90**, 2735.

6. R. I. Walter and E. C. A. Ojadi, *J. Phys. Chem.*, 1993, **97**, 13308.

7. A. S. Sadjadi, R. I. Walter, and J. S. Harwood, *J. Phys. Chem. A*, 1997, **101**, 9948.

8. M. O. Senge in *The Porphyrin Handbook*, ed. K. M. Kadish, K. M. Smith, and R. Guilard, Academic Press, Burlington, MA, 2000, vol. 1, ch. 6.

9. M. S. Somma, C. J. Medforth, N. Y. Nelson, M. M. Olmstead, R. G. Khoury, and K. M. Smith, *Chem. Commun.*, 1999, 1221.

10. M. O. Senge and W. W. Kalisch, *Zeitschrift für Naturforschung*, 1999, **54**, 943.

Table 1. Summary of NMR and crystallographic data for porphyrins **4-7**.

Porphyrin/Acid	$\Delta G^{\ddagger}_{EX}$[a] (kJ mol^{-1})	ΔC_b (Å) (dication)[b,c]	Monocation Observed?[d]	ΔC_b (Å) (dication-free base)[c,e]
oep/Picric	46	0.06 - 0.72 (4)	Yes	0.00 - 0.64
/Trifluoroacetic	54		Yes	
/Hydrochloric	61		Yes	
tpp/Picric	63	0.85 - 1.08 (4)	No	0.62 - 0.94
/Trifluoroacetic	68		No	
/Hydrochloric	78		No	
t(Bu^t)p/Picric	82	1.29 (1)	No	1.15
/Trifluoroacetic	82		No	
/Hydrochloric	[f]		No	
oetpp/Picric	>89	1.31 - 1.38 (4)	Yes	0.14 - 0.21
/Trifluoroacetic	xx		Yes	
/Hydrochloric	xx		Yes	

[a]Activation energy for proton exchange between the dication and free base (tpp, t(Bu^t)p, and oetpp) or the dication and a mixture of the free base and monocation (oep). NMR studies were conducted in CD_2Cl_2, $CDCl_3$, $CDCl_2CDCl_2$ or toluene-d_8.

[b]Number in parentheses is number of crystal structures. Note that the dications typically also contain a small amount of ruffle distortion (pyrrole twisting).

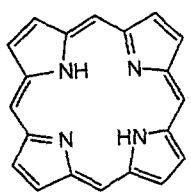
[c]Data taken from references 8-10.

[d]NMR studies were conducted in CD_2Cl_2. Monocation observed indirectly via exchange broadening of signals for the free base porphyrin in the case of oep with trifluoracetic and hydrochloric acid.

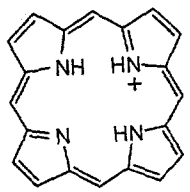
[e]ΔC_b for free base t(Bu^t)p was corrected for the large amount of ruffling distortion present.

[f]Free base t(Bu^t)p was unstable when exposed to hydrochloric acid.

Structures



1



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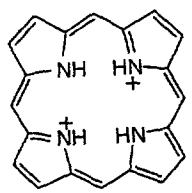

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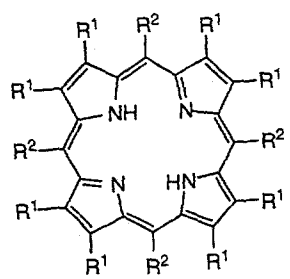


4 $R^1 = H$, $R^2 = C_6H_5$

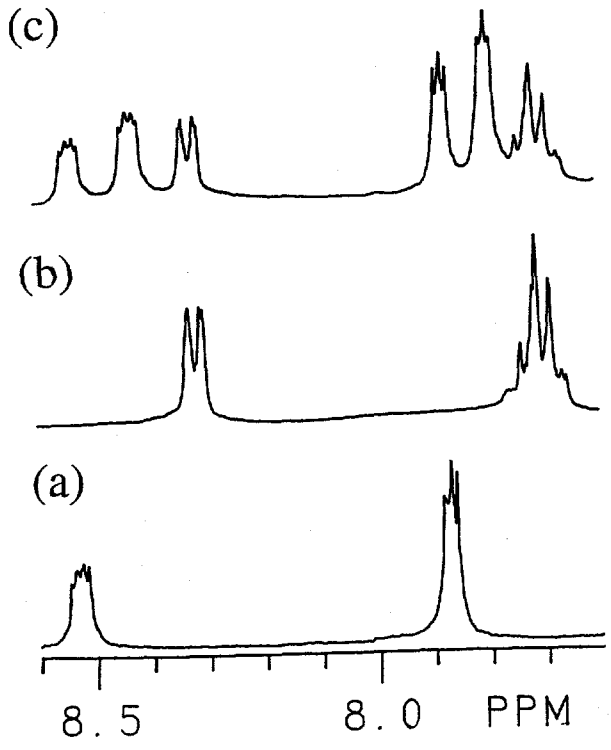
5 $R^1 = CH_2CH_3$, $R^2 = H$

6 $R^1 = CH_2CH_3$, $R^2 = C_6H_5$

7 $R^1 = H$, $R^2 = C(CH_3)_3$

Figure Caption

Figure 1 Portions of the 300 MHz ^{1}H NMR spectra of the oetpp dication picrate salt (a), free base oetpp (b), and a mixture of the oetpp dication picrate salt and free base oetpp (c). Spectra were measured at 298 K in CD_2Cl_2.


(c)
(b)
(a)
8.5
8.0
PPM